Acetabular bone loss in revision total hip arthroplasty (THA) is a challenge. To gain sufficient stability and adequate position of the new acetabular component, several surgical procedures have been reported. Most authors agree on the fundamental importance of initial stability and primary fixation. There are 4 principle ways to compensate for acetabular bone loss: a high hip center by using a larger cup, structural or morselized bone grafting, and trabecular metal augments.

Acetabular bone defects in revision hip arthroplasty are classified according to American Academy of Orthopaedic Surgeons into: segmental (type I), cavitory (type II), combined cavitory and segmental (type III), and pelvic discontinuity (type IV) [1]. Segmental defects can be repaired with structural allografts or metal meshes combined with impaction bone grafting (IBG) or left undone—if adequate bone stock exists for a stable cementless fixation [2–6]. Structural grafts may be combined with a load-shielding reinforcement ring during graft incorporation [7]. Another option is to use a large cementless cup in contact with native bone, anchored with screws and combined with some morselized bone graft in limited osteolytic defects [8,9]. In cases with segmental bone defects, morselized and impacted bone allograft may be supported by a reinforcement ring, metal meshes, or trabecular metal augments [10]. An oblong cup will restore the center of rotation without restoring bone stock [11].
The biological response to, and fate of, structural vs morselized bone allograft differ fundamentally. Structural allografts rarely incorporate completely and may eventually resorb. Mechanical stability is mandatory for successful IBG; insufficient support for graft impaction and for the acetabular component predicts failure. IBG may have the problem of inadequate cup support, if the impaction technique is inadequate, or if a too-weak mesh is used for restoring a segmental defect. A rigid reinforcement ring combined with IBG has the disadvantage of stress-shielding the bone graft from cyclic loading and hence reduces bone formation stimuli. Results from various reconstruction methods are summarized in Table 1.

The concept of IBG consists of important details that can be performed in various ways, but the 2 major prerequisites contributing to bone healing are graft compression and stability. The original method for acetabular IBG is described by Slooff et al.

The purpose of the study herein is to report the medium-term to long-term clinical and radiological results of a novel technique, using a flexible, perforated titanium plate (to repair segmental acetabular bone defects) and a thin titanium shell (for stabilizing and compressing the impacted bed of particulated bone homograft).

Materials and Methods

Patients

Between 1998 and 2012, 930 cases were identified at Gavle and Sunderbyn hospitals (Sweden) as having undergone an acetabular component revision. In 6 of those cases, augments were used in combination with an uncemented cup according to the surgeon’s preference. The only indication for cages was pelvis dissociation diagnosed preoperatively (n = 10). One hundred seventy of the cases were scheduled for IBG. The indication for using the IBG method was cup loosening and osteolysis resulting in an enlarged acetabulum. Among the cases planned for IBG, another 3 cases of pelvic dissociation were diagnosed only intraoperatively. According to the surgeon’s preference, the IBG method, without using a cage, was used also in these cases. One hundred fifty-six of the IBG patients had mechanical loosening with bone loss. Fourteen operations were performed secondary to a periprosthetic infection and osteolysis. In 78 cases, the femur component was revised as well. Nine surgeons in 2 institutions performed the revision THAs. For demographics inclusive bone loss, see Table 2.

Surgical Technique

Bone grafts were taken fresh from frozen femoral heads harvested at primary arthroplasty for hip osteoarthritis and stored...
The femoral heads were cleaned from cartilage and fibrous tissue and the bone morselized in a Howex milling machine (Gävle, Sweden). The bone chips were up to $2 \times 4 \times 8$ mm. The graft was defatted by repeated rinsing in warm saline solution. All patients had received systemic antibiotic prophylactics during surgery and were operated using a standard posterolateral approach in the lateral decubitus position. After removal of the failed acetabular component, biopsy specimens from the membrane were sent for bacterial culture. Segmental defects of the acetabulum (Fig. 1) were repaired by a flexible 0.8 mm thick titanium plate, perforated with 4 mm holes (Fig. 2) (Waldemar Link GmbH & Co, Hamburg, Germany). The tear drop of the acetabulum was identified and efforts were made to restore the center of rotation to a normal position. Curettes and reamers were used to remove any membrane from the acetabular bone bed. A hard graft impaction was performed using acetabular impactors from the Lubinus SP II Impaction Instrument Set (Waldemar Link GmbH & Co). These impactors are fully equipped with a 1-mm high circular thread-like microstructure to enhance a hard impaction (Fig. 3). On top of the impacted acetabular graft bed, a titanium shell of 2-4 mm larger size compared with the used impactor was used (Fig. 4A and B). The shell (Waldemar Link GmbH & Co) was anchored with multiple, small titanium screws for further compression and stabilization of the graft bed. The titanium shell of 0.8- or 1.0-mm pure titanium is fully perforated with 4-mm holes to allow for a free screw fixation and for cement perforation into the graft bed. The shell is available in sizes 48-58 mm of every other mm increments. The shell has been commercially available since 1998. Finally, additional graft impaction was performed in the space in-between the shell and the titanium plate (Fig. 5). All surgical procedures included global IBG in the acetabulum. An acetabular polyethylene cup, 2-4 mm smaller than the inner diameter of the titanium shell, was cemented inside the shell with Palacos cum Gentamycin bone cement using third-generation cementation technique. All patients were treated postoperatively for 9-21 days with low-molecular-weight heparin as a thrombosis prophylactic. The patients were mobilized on the first or second day after surgery to walk with ambulatory help. Most of the patients were allowed free weight bearing, according to the surgeon’s choice.

**Follow-Up**

The patients were followed up retrospectively, by extracting preoperative clinical classification from preoperative medical journals at the 2 hospitals. Follow-up was performed after a mean of 7 years (standard deviation 2.8). Follow-up level divided the patients into 4 groups: (1) clinical and radiological follow-up was performed (95 cases); (2) patient was analyzed by radiography, declined a visit, but was interviewed by telephone (26 cases); (3) patient was analyzed by radiography, declined both a visit and telephone interview (2 cases); and (4) patient was deceased (33 cases), but medical records including the latest radiography were examined and any reoperation noted. Of the 170 cases, 1 was lost to follow-up and 2 died shortly after surgery of unrelated causes. These 2 patients died before any follow-up was done, and are therefore regarded as “lost to follow-up” (Fig. 6).

All preoperative and postoperative radiographs were available. Graft incorporation was assessed according to Gie et al [18]. The outer diameter of the femoral head was measured to correct for magnification in the radiographs. The correction of the hip center of rotation was measured from an inter-teardrop line or a bi-ischial line in the y-axis, and in the x-axis from a line from the symphysis to the sacrum center [19,20]. The correction was measured from the center of the prosthetic head on calibrated, plain antero-posterior radiographs taken pre- and post-operatively. Cup migration was analyzed from the post-op and follow-up preoperative radiographs.
radiographs. The difference was classified as 4-9 mm or more than 9 mm. Clinical outcome was analyzed using the Charnley modification [21] of the Merle d’Aubigné-Postel classification. Mechanical failure was defined according to DeLee and Charnley [22].

Statistical methods

The follow-up period started on the day of implantation of the THA and ended on the day of revision, death, or last available follow-up measurement. For estimating the survival rate, the Kaplan-Meier method was used [17]. The endpoints were mechanical loosening of the acetabular component or reoperation for any reason; 95% confidence intervals for the survival rates are given. Numerical results are presented as mean values (standard deviation), unless otherwise stated. The statistical software, R version 3.2.3 (R Core Team, 2015) was used in the analyses.

Results

Among the 167 cases, 12 cases were assessed failures of which 11 had been revised. Five patients were revised due to mechanical loosening after 5-7 years. Another patient had circumferential radiolucent lines and was diagnosed with a possible loose cup. This patient had no discomfort and was not planned for revision surgery at the time of follow-up. Two failures were septic (both after 1 year) and 3 were revised for recurrent dislocations (after 4 months, 2, and 6 years respectively). Another case was revised after 2 months due to dissatisfactory cup anteversion. There were no surgical complications that could be related to the technique. No patient suffered from permanent nerve palsy or a wound infection requiring surgical intervention.

The Kaplan-Meier analysis, with reoperation for aseptic loosening as the endpoint, revealed a survival rate of 95% at 10 years. Kaplan-Meier analysis with reoperation for any reason as the end point, revealed a survival rate of 92% (Fig. 7). The mean Merle, Aubigne and Postel score was 10.8 pre-operatively and 16.4 at follow-up. No patient declined in clinical score over time. All patients interviewed by telephone declared normal hip function without hip pain or discomfort.

Graft healing was assessed according to Gie [18]. Radiographic evaluation showed generally a healing appearance; the graft-host border disappeared over time indicating transformation of graft into living bone (Fig. 8). Of the 143 cases with accessible radiographs at follow-up, 66 had an unchanged graft appearance, 17 had trabecular remodeling, 20 had trabecular incorporation, 13 had cortical repair, 14 had cortical repair and trabecular remodeling, 9 had cortical repair and trabecular incorporation, 4 had local graft resorption, and 14 could not be classified because of insufficient x-ray quality. Four of the cases had a cup migration (3, 4, 4 and 9 mm). The ability of this technique to restore the hip center of rotation was assessed for 113 of the cases (Table 3). Length of correction cases could not be measured for 57 of the cases because of technical errors in the radiographs. Those errors did not affect assessment of possibly implant loosening.
Discussion

There were 2 important findings in this study. First, the overall complication rate was low. We used relatively small-sized implants to convert non-contained defects to contained ones. Larger support implants like metal rings increase the risk for nerve and muscle damage. Consequently, complications like Trendelenburg limp, dislocation, and septic failure become more common [7].

The second finding was the low rate of mechanical failure despite the advanced bone deficiencies. This might be a coincidence; a longer follow-up time might have revealed a higher failure rate. We do, however, believe that our attention to biological principles of graft healing, contributed to the good results. Incorporation of morselized bone graft is comparable with healing of metaphyseal fractures. Bone formation differs between metaphyseal and diaphyseal fracture healing [23]; the bone heals swifter when trabeculae are present [24,25]. In revision THA, morselized homo graft revascularizes more quickly and more completely than cortical homo graft.

Furthermore, the bone-healing stimulating agent; bone morphogenic protein-7 (BMP-7) is released from frozen human allograft in a linear way when put under increasing strain; thus, frozen bone allograft is biologically active and osteoinductive when compressed. A compressing titanium shell may increase stability and BMP-7 release. The shell will also enable further impaction within segmental defects, that is, between the lateral plate and the compressing shell (Fig. 6). In a positron emission tomographic study, bone formation has been shown to occur even in this compromised area at 4 months postoperatively [26]. Direct apposition of new bone on surfaces of dead graft trabeculae after IBG has been shown in a histology study [27].

Slooff et al [17] introduced the technique in 1984 to reconstruct acetabular bone defects by impacting particulate bone allograft. Garcia-Cimbrelo et al [28] found that clinical outcome correlates with type and magnitude of acetabular bone loss. The most important factor associated with mechanical failure was using a lateral mesh, which had an increase of hazard ratio of 2.94 [13]. The same finding was noted by Gilbody et al [14] and Rigby et al [29]. In a 12-year follow-up of 304 cases with IBG and cemented fixation, the hazard ratio increased to 3.54-5.11 for rim or wall meshes.

The presence of severe acetabular defects is more demanding and may have poorer outcomes. In the present study, we could, however, not see a correlation between mechanical failure and type or size of acetabular bone defect. Of 5 mechanical rerevisions, 3 had combined defects and 2 had cavity defects. In the present series, 56% of the cases had combined segmental and cavitary bone defects at the time of revision surgery. Reconstruction of a segmental wall defect needs to be supportive—not only during the graft impaction procedure—but also for load during the postoperative graft-healing period. Any reinforcement device for an acetabular rim defect must last throughout this time. Garino et al [30] presented a study using weaker metal mesh (Howmedica International, London, England) for repairing segmental acetabular bone defects in combination with IBG. After a mean of 4-year follow-up, 3 of 21 cases were revised because of aseptic loosening and another case for infection. This result is still acceptable considering the presence of severe acetabular bone defects. The segmental defects in the present series were converted to contain ones using perforated titanium plates before graft impaction. No titanium plate used in this report failed by loosening or breakage despite the size of segmental bone defect.

Trabecular metal for the repair of segmental defects followed by IBG and a cemented cup has shown good results at 4-year follow-up [10]. However, further bone resection from the compromised acetabulum is needed to fit the tantalum augment, which might be considered a disadvantage. Good results have also been shown by van Egmond et al [31] for this strategy. In their study, 25 of 27 cases had type III defect and 2 had type IV. After 10 years, the survival rate was 95% as end point revision for aseptic loosening. Rigby et al [29] investigated 339 hips operated with the IBG method and cemented cups. Their study consisted of 261 revisions with a mean follow-up of 6.1 years. The survival rate was 92% defined as rerevision caused by aseptic loosening.

In contrast, van Haaren et al [32] reported a survival rate of 72% at 7.2 years with end point rerevision for aseptic loosening using IBG and a cemented cup. Of these cases, 68% had uncontained defects.

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<td>Length and Numbers of Corrected Hip Rotation Centers During Surgery.</td>
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Fig. 7. Kaplan-Meier survivorship curve, with failure for any reason.

Fig. 8. Radiograph of acetabulum 6 years after revision total hip arthroplasty (THA) of a type III defect repaired by a titanium plate, impaction bone grafting (IBG), a titanium shell, and a cemented poly cup.
acetalicular defects repaired by metal meshes. A large cementless cup with screws combined with morselized bone graft is another alternative. This method was recently reported with 13% mechanical failure (rerevision or radiological failure) after a mean follow-up of 9 years [9].

However, when a shelf allograft was used instead of IBG to reconstruct a column defect (Paprosky type IIIa), Sporer et al [36] reported 30% mechanical failure at 16 years, suggesting that structural allograft unlike morselized, may resorb in the long run. A structural allograft protected by an antiprotrusion cage is yet another alternative for major column defects; for these, 24% resulted in rerevision or clinical failure at a mean follow-up of 4.6 years [35].

The price for the present implants (shell, rim plate, cement, poly cup, and bone graft) is substantially cheaper compared with the alternatives of an uncemented cup, possibly together with augments or an antiprotrusio cage together with cement, poly cup, and possibly bone graft. If using a patient-specific 3-D printed implant, the price would be much higher. We do not believe the concept of reinforcement metal rings to be combinable with IBG [36]. A segmental defect must be converted to a contained defect before impaction grafting; otherwise, the inserted graft cannot be impacted. Furthermore, a rigid metal ring on top of morselized bone graft omits the graft-healing stimulus mediated by body load [16]. The ring needs a bone support [7] that is not provided by particulate bone graft. Buttaro et al [37] reported a failure rate of 37% at 24 months for bone defect types III and IV (American Academy of Orthopaedic Surgeons) with a rigid reinforcement ring in combination with IBG. For results from the literature on different acetabular revision methods, see Table 3. IBG is considered technically demanding and the method includes a learning curve [38]. The graft distributing method called reverse reaming—when an acetabular reamer is driven in reverse direction towards particulated bone graft—is inadequate in terms of impaction force. For a sturdy grip of the chips during impaction, the acetabular impactor used in this series was equipped with a microstructure of 1-mm high circular threads (Fig. 3). This prevents the chips from slipping up along the sides of the acetabular impactor as a result of the impaction blows, and instead being thoroughly impacted for shaping a stable graft bed. Cement floating around the graft chips completely encapsulates them and counteracts bone ingrowth. This phenomenon may be diminished by using the titanium shell for complementary graft compression. We believe the use of the titanium shell may standardize the surgical procedure. The multiple holes of the shell allow cement to penetrate the bone chips in contact with the shell (Fig. 9), as when cementing on an impacted graft bed without using the shell. We agree with other authors [39] in the good clinical results and the ease with which bone defect irregularities can be filled using impaction grafting, in contrast to the use of structural allografts.

**Factors Contributing to Success of IBG**

_Graft Preparations_

Initial stability will increase with bigger and defatted bone graft particles [40,41]. Impaction should be performed with dedicated instruments and firm hammer blows [42].

_Containment_

Any segmental defect has to be safely repaired (covered from the outside), for example, by using a thin perforated titanium plate anchored with multiple small screws. This converts the noncontained defect to a contained one to provide a stable counterhold for a hard graft impaction. It also adds stability to the construct, including the polyethylene cup, during the postoperative healing period.

_Stability_

Rigorous impaction of big defatted bone chips increase stability [40,41]. Compression of spongious bone allograft that has been frozen results in the release of BMP-7 from the allograft bone [43]. BMP-7 stimulates bone-healing.

_Load_

Load-bearing in an animal model has shown that new bone forms in impacted and morselized allografts [44]. Therefore, it is advantageous for the graft not only to be rigorously impacted during the surgical procedure, but also to be assured of continuous graft compression during the postoperative healing period. The titanium shell used in the present series contributes to such a compression.

**Conclusion**

Revision acetabular arthroplasty with IBG and the described compression shell was safe and did not result in any complications related to the implanted shell or the titanium rim plate. The method resulted in excellent medium-term to long-term clinical results and can be recommended as a standard procedure to secure the graft bed in the IBG method with a cemented cup. The method was capable of reconstituting the normal center of rotation. It also reconstituted bone lost secondary to prosthetic loosening and produced a stable base for the simultaneous insertion of the arthroplasty cup.

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All authors were involved in collecting and processing the data and writing the manuscript. Nine surgeons had performed the
surgeries. Gavle and Sunderby hospitals are Swedish, secondary experience with IBG in revision THA.

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